Chiral symmetry restoration and Medium Effects in Relativistic Heavy-Ion Collisions*

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Theoretical and experimental studies of hot and/or dense matter, such as is created in high-energy heavy-ion collisions, and encountered in compact objects in astrophysics, constitute one of the most active frontiers in nuclear physics. In these Lectures, we discuss various approaches to the description of hot and/or dense matter, including the simple Skyrme-type parameterization and relativistic Walecka-type models, as well as microscopic Dirac-Brueckner and QCD sum rule approaches. As density and/or temperature of the hadronic system increases, chiral symmetry is gradually restored, as indicated by the decrease of quark condensate. This has profound effects on the properties of hadrons, especially their masses. We review various theoretical predictions for hadron properties in dense matter. Experimentally, possible medium modifications of hadron properties can be studied through the measurements of particle spectra, flow, and particularly, electromagnetic observables. Particle production, especially the production of rare particles such as kaons, vector mesons, and antiparticles, provides useful insight into heavy-ion collision dynamics, and hadron properties in dense matter. Collective flows of various kinds are important observables in heavy-ion collisions. They probe essentially the entire reaction process, and thus are very useful for the determination of the reaction dynamics. They also reflect the properties of hadrons in dense matter. We discuss flow of nucleons, pion, as well as kaons, in heavy-ion collisions from SIS to SPS energies (1-200 AGeV). Again, we shall emphasize what we can learn about the properties of dense matter and in-medium properties of hadrons from the flow study. Electromag-

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netic signals, namely photon and dileptons spectra, are considered penetrating probes that may carry undistorted information about the early stage of high-energy heavy-ion collisions. The observation of the enhancement of low-mass dileptons by both the CERES and HELIOS-3 collaborations has stimulated a large amount of theoretical activity. We discuss various theoretical calculations of dilepton production in heavy-ion collisions. We then consider various medium effects that have been proposed to explain the enhancement. Another piece of experimental data from SPS that have been discussed extensively is the single photon spectra from the WA80 collaboration. We review various hydrodynamics and transport model calculations for direct photon production in heavy-ion collisions.

I. INTRODUCTION

It is generally accepted that quantum chromodynamics (QCD) is the ultimate theory of strong interactions [1]. At low energy scale relevant for conventional nuclear physics, QCD exhibits two important and related features, one is the color confinement and the other is approximate chiral symmetry and its spontaneous breaking. The latter manifests itself in the smallness of current quark masses and the non-vanishing quark condensate in vacuum. The magnitude of the quark condensate, $\langle\bar{q}q\rangle_0 \approx \langle\bar{u}u\rangle_0 \approx \langle\bar{d}d\rangle_0$, can be estimated from the Gell-Mann−Oaks−Renner relation,

$$m_\pi^2 f_\pi^2 = -2m_q\langle\bar{q}q\rangle_0. \tag{1}$$

In the above, $m_\pi \approx 138$ MeV and $f_\pi \approx 93$ MeV are the pion mass and decay constant, respectively; and $m_q = (m_u + m_d)/2 \approx 5.5$ MeV is the average up and down quark masses. The quark condensate in vacuum thus has a value $\langle\bar{q}q\rangle_0 \approx -(245\,\mathrm{MeV})^3$.

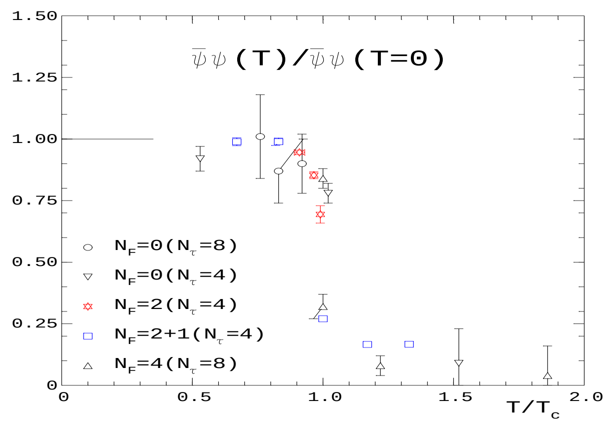

FIG. 1. Temperature dependence of quark condensate in the lattice QCD simulation. The different symbols correspond to different number of flavors and lattice size. (from Ref. [3])

As the density and/or temperature of a hadronic system increase, this spontaneously broken symmetry is expected to be partially restored, so the quark condensate would decrease with increasing density and/or temperature. At zero baryon chemical potential, the decrease of quark condensate with increasing temperature has been observed in lattice QCD simulations [2–4] as well as in calculations based on the chiral perturbation theory [5,6]. In Fig. 1 we show the quark condensate normalized to that in the vacuum as a function of the normalized temperature, obtained in lattice QCD simulations with various number of flavors and lattice spacing. The quark condensate shows weak dependence on the temperature up to about $0.9T_c$. Around the critical tempereture the quark condensate decreases very rapidly, indicating chiral symmetry restoration.

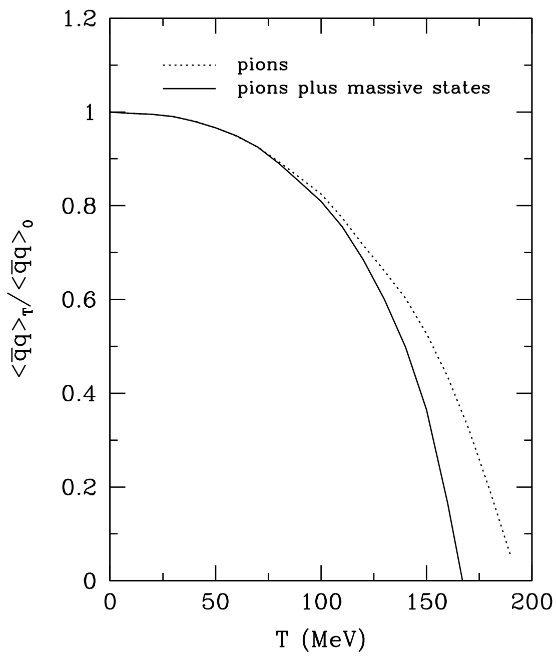

FIG. 2. Temperature dependence of quark condensate in the chiral perturbation theory. The dotted curve includes pions only, while the solid curve includes massive resonances as well. (from Ref. [5])

In the chiral perturbation theory, quark condensate is found to drop more rapidly at low temperatures than that observed in the lattice QCD simulation [5]. Expanded in terms of temperature, the leading contribution to the change of quark condensate is the T^2 term,

$$\frac{\langle \bar{q}q \rangle_T}{\langle \bar{q}q \rangle_0} = \left[1 - \frac{n_f^2 - 1}{n_f} \left(\frac{T^2}{12 f_\pi^2} \right) - \frac{n_f^2 - 1}{2 n_f^2} \left(\frac{T^2}{12 f_\pi^2} \right)^2 + O(T^6) \right], \tag{2}$$

where n_f is the number of flavors. The results from Ref. [5] in the limit of zero quark mass are shown in Fig. 2 as a function of temperature. Again it is seen that the quark condensate decreases with increasing temperature, implying the gradually restoration of the chiral symmetry.

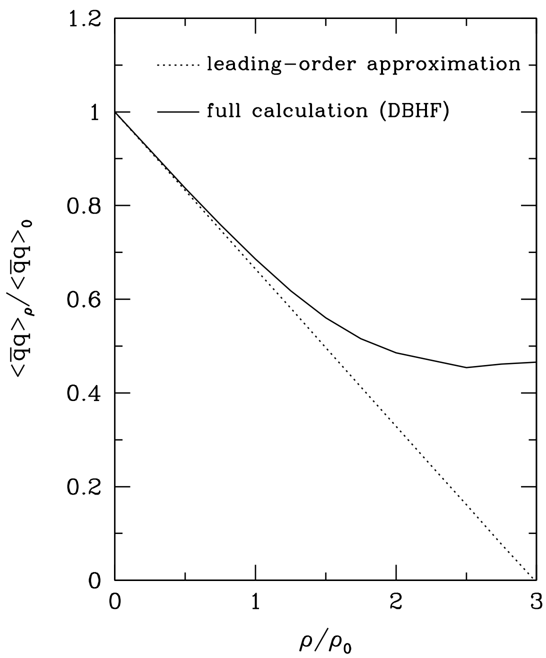

FIG. 3. Density dependence of quark condensate. The dotted curve gives the leading order result, while the solid curves include the higher-order contributions in the DBHF approach. (from Ref. [11])

At finite baryon density, model-independent studies using the Feynman-Hellmann theorem [7,8] have shown that the ratio of the quark condensate in medium to its value in vacuum in the leading order in density is given by

$$\frac{\langle\bar{q}q\rangle_\rho}{\langle\bar{q}q\rangle_0} \approx 1 - \frac{\Sigma_{\pi N}}{f_\pi^2 m_\pi^2}\rho_N, \tag{3}$$

where ρ_N is the nuclear density and $\Sigma_{\pi N} \approx 45$ MeV is the πN sigma term. At normal nuclear matter density $\rho_0 \approx 0.16$ fm^{-3}, the condensate is seen to decrease already by about 1/3. Higher-order contributions to the quark condensate in nuclear matter due to nucleon-nucleon interactions have been studied using various models [8–13]. It is found that at normal nuclear matter density they change the leading-order result by only about 5% [11,13]. At higher densities, the results, however, depend sensitively on the model for nuclear matter and on the derivatives of meson masses to the current quark mass, which are not well known. We show in Fig. 3 the quark condensate as a function of density. The dashed curve gives the leading order results, and solid

curve includes higher-order corrections based on the Dirac-Brueckner-Hartree-Fock (DBHF) calculation [11].

FIG. 4. QCD phase diagram in the temperature-density plane.

Closely related to the chiral symmetry restoration is the deconfinement phase transition, namely the transition from the non-perturbative hadronic matter at low energy densities to the perturbative quark gluon plasma (QGP) at high energy densities where the color degrees of freedom are no longer confined. In the lattice QCD simulations, this phase transition is predicted to occur at a critical energy density of $\varepsilon \approx 1 - 3$ GeV/fm^3. The search for and the study of the properties of the QGP is one of the most active fields in nuclear physics [14]. In Fig. 4 the QCD phase diagram in the temperature-density plane is shown. Conventional nuclear physics studies the nuclear matter around normal nuclear matter density and temperature close to zero. As the temperature of the system increases, the nuclear matter may undergo the so-called liquid-gas phase transtion, and mesons, mainly pions, are produced. The system can be described as an interacting hadronic gas. At even higher tempearture, the hadronic system may undergo the deconfinement phase transition into the QGP. The extremely high temperature and low net baryon

system might correspond to the situation as encountered in the early universe seconds after the big-bang explosion. In the other extreme, the nuclear matter can be compressed to many times the normal nuclear matter density, while the temperature is kept relatively low. This corresponds to the situation encountered in the cores of neutron stars. In relativistic heavy-ion collisions, ususally both baryon density and temperature are increased.

To learn about thermodynamics of hadronic matter and GQP, especially the so-called equation of state (EoS), is one of the primary motivations of relativistic heavy-ion physics. The EoS is usually expressed in terms of the energy density or the pressure of the system as a function of temperature and/or density. At low temperatures, the system consists mainly of nucleons, which interact with each other through effective nucleon-nucleon interactions. A simple yet quite useful phenomenological model for the EoS of the dense nuclear matter is the Skyrme model [15–19]. Relativisitc models such as Walecka model and its various extensions [20–22] have also been used quite often in the description of dense matter. More microscopically, the nuclear matter EoS can also be obtained in the framework of the DBHF approach [23–25], based on the realistic nucleon-nucleon interaction such as the Bonn potential [26]. As the temperatrue of the system increases, mesons are excited and need to be taken into consideration explicitly. In the extreme case of high temperature and low net baryon density, the system can be treated as an interacting meson (chiefly pions) gas. The EoS of such a system has been studied in both the chiral perturbation theory and effective meson exchange models. The EoS of the hot and dense matter can also be obtained by extending Walecka-type model to finite temperature. Finally, the EoS can also be simulated on the lattice. We will discuss the modeling of hot and/or dense matter in Section 2.

The study of hadron properties in hot and dense matter is also a very interesting topic [27–30]. The question of how the decrease of quark condensate in hot and/or dense matter manifects itself in experimental observables is still under intense debate. One possibility is that the decrease of quark condensate in medium may lead to reduced hadron masses as shown in QCD sum-rule studies [31–33]. We will review in Section 3 the various theoretical prediction for the in-medium properties of hadrons. We will concentrate on the chiral perturbation theory for kaon and antikaon in-medium properties, and QCD sum rule for vector meson properties.

The only way to create 'macroscopic', strongly interacting systems at finite temperature and/or density in laboratory is through collisions of heavy nuclei at high energies. Experiments carried out at various bombarding energies, ranging from 1 AGeV (BEVALAC, SIS), to 10 AGeV (AGS) and 200

AGeV (SPS), have shown that one can indeed generate systems of large baryon density but moderate temperature (1 AGeV), systems of both high baryon density and temperature (10 AGeV), and systems of high temperature but relatively small baryon density (200 AGeV). Future experiments at RHIC-BNL and LHC-CERN colliders are expected to create matter at extremely high temperature which is essentially baryon free. Therefore, the entire region of the QCD phase diagram can be investigated through the variation of the bombarding energy [34–36].

Unfortunately, the dynamics of heavy-ion collisions is very complex, involving a violent initial compression, which is then followed by a relatively slow expansion and finally reaches the freeze out when particle interactions become unimportant. The entire reaction typically lasts for about a few tens fm/c. The interesting physics of chiral symmetry restoration and QGP formation can only be studied for a few fm/c during the early part of the expansion stage when both the density and temperature of the hadronic matter are high. This stage of the collision can in principle be probed by detecting the emitted electromagnetic radiation such as the real and virtual (dilepton) photons. However, both are not easy to measure due to their small rates. Furthermore, they can also be produced from initial hard collisions and final hadron decays, and this makes it difficult to extract the signals from the hot dense matter. What are usually measured in heavy-ion experiments are instead the momentum distributions of hadrons, such as the nucleon, nuclear clusters, pion, kaon, etc., which are mostly ejected from the colliding system at freeze out. To infer what have happened in the initial hot dense matter from the final hadron phase space distributions requires thus a model that can describe the whole collision process. Indeed, various transport models have been developed during the past ten years for this purpose. We note that a number of good review articles are available on both relativistic and nonrelativistic transport models for heavy-ion collisions at various energies [37–47].

One type of transport models that are based on the Walecka-type σ-ω model is particularly suitable for the study of hadron properties in dense matter [48–52]. In this model, the effective masses of hadrons are reduced by the scalar potentials while their energies are shifted by the vector potential. When the density of the system is high, the hadron masses are reduced and converted into the field energy. As the system expands, the hadrons gradually regain their masses from the field energy. This model provides a thermodynamically consistent framework to treat the change of hadron properties in hot and/or dense matter. This review will thus discuss mainly the results obtained in the relativistic transport models based on the Walecka-type models.

In addition to a good transport model, we also need to identify a set of good observables that can be used to study the hadron in-medium properties. The change of hadron masses should affect their production thresholds, and thus their yields and spectra in heavy-ion collisions. The threshold effects are expected to be most pronounced for particle production at the so-called subthreshold energies, namely the beam energies at which these particles cannot be produced in free space nucleon-nucleon interactions simply because of the lack of energy. Usually, the particle production cross sections near the thresholds strongly increase with the available energy, thus a change of hadron masses will lead to very dramatic change in the particle production cross sections. In Section 4 we will discuss particle production in heavy-ion collisions from SIS to SPS energies, but concentrate on that at SIS energies.

Another related, but more subtle observable that is useful for the study of hadron in-medium properties is the collective flow of particles and fragments. Up to now mainly three types of flow have been investigated experimentally and theoretically, namely, the in-plane flow, out-of-plane flow, and radial flow. In heavy-ion collisions, dense matter provides strong mean field potentials for hadrons. When propagating in these mean field potentials, hadron momenta are modified which will be reflected in their final momentum spectra, and therefore in various flow observables which are the different projections of the competely momentum distribution. We will discuss flow observables in Section 5. Again we will concentate on the results at SIS energies, but will also mention lower NSCL-MSU energies, and higher AGS and SPS energies.

Both hadron spectra and flow are subject to strong final-state interactions. On the other hand, electromagnetic observables, such as photon and dilepton spectra, are considered penetrating probes of the early stage of heavy-ion collisions since they interact with the hadronic environment relatively weakly. They might carry undistorted information about the densest and hottest phases of the heavy-ion collisions where chiral symmetry restoration and/or GQP formation are expected. Moreover, since dilepton mass spectra reflected directly vector meson masses, they are most ideal for the study of the in-medium masses of vector mesons, especially that of the rho meson. We will discuss the electromagtic observables in Section 6.

This series of lectures ends with a summary and outlook in Section 7.

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